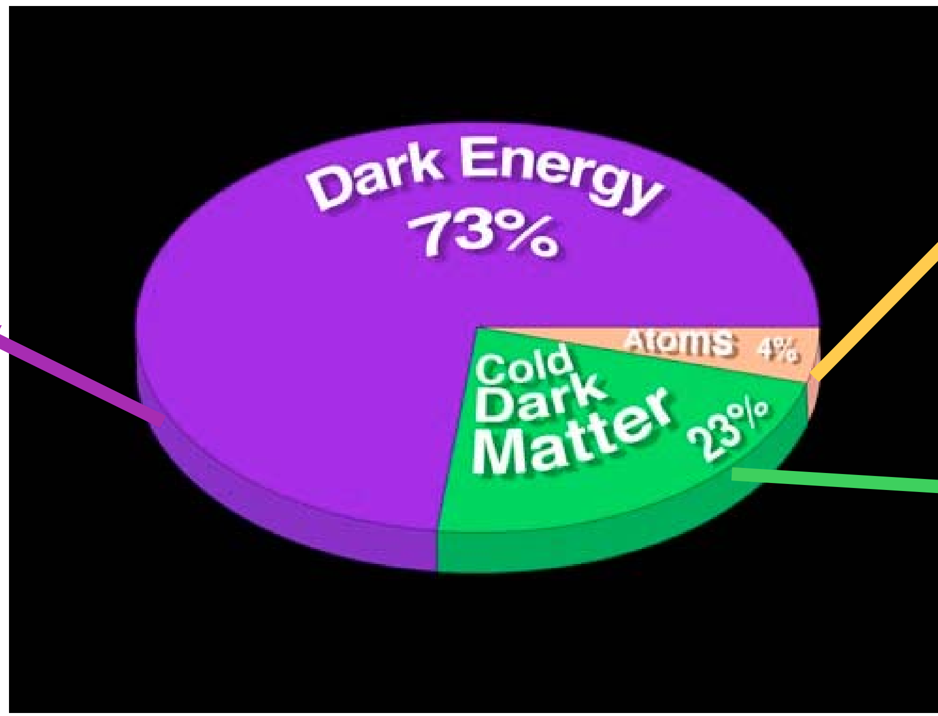
Dan Bauer
CDMS Project Manager
Long-Range Planning Meeting on
Fermilab Astrophysics
October 14, 2003

The Hunt for WIMPs

Stuff we have no clue about



The Universe, according to WMAP

Stuff we know about

Stuff predicted by theory:
WIMPS
Axions

Talk today mostly limited to direct detection of WIMPS

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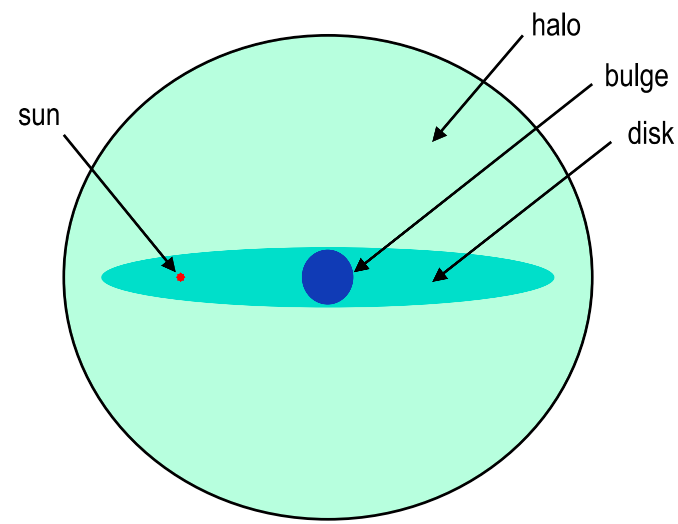
Direct Detection of WIMPs

WIMPs **elastically scatter** off nuclei in targets, producing **nuclear recoils**, with $\sigma_{n\chi}$ related roughly by crossing to σ_A(~10^{-38} cm^2)

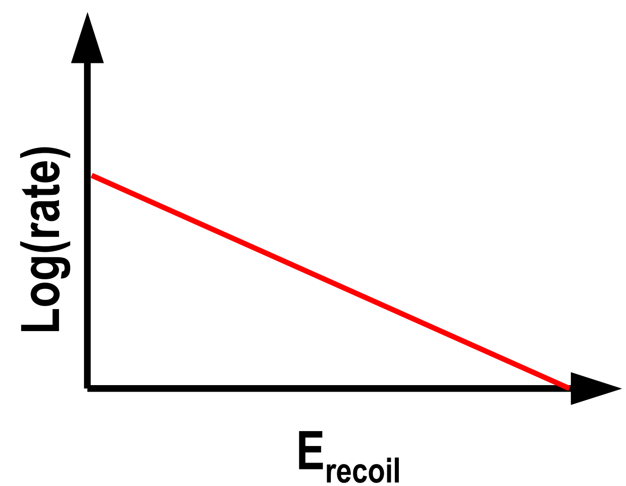
- Slow velocities ⇒ large de Broglie λ ⇒ coherent interaction with all nucleons
  - Spin-independent interaction $\propto A^2$
  - Spin-dependent needs target with net spin
- Lose coherence for largest-A targets



The Milky Way

Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo

- Standard assumptions: isothermal and spherical, Maxwell-Boltzmann velocity distribution
- V_0= 230 km/s, v_{esc}= 650 km/s,
- ρ = 0.3 GeV / cm^3
- Not the only possible assumptions, of course!



Energy spectrum of recoils is featureless **exponential** with $\langle E \rangle$ ~ 50 keV

Rate (based on $\sigma_{n\chi}$ and ρ) < **1 event / kg target material / day**

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Experimental Challenges for Direct Detection of WIMPs

- keV energy threshold
  - Sensitivity to low mass WIMPs
- Low radioactive contamination
  - Screening/purification of materials
  - Clean surfaces
    - Dust (U/Th/K)
    - Radon (daughter implantation)
- Background suppression
  - Deep sites (reduced cosmic ray flux)
  - Passive/active shielding
- Residual background rejection
  - Active nuclear recoil discrimination
  - Sensitivity improves:
    - Linearly with target mass and exposure time if no background
    - As $1/\sqrt{MT}$ by statistical subtraction of background
    - No further improvement if systematics of background subtraction dominate

- Signal Features
  - Location and type of interaction
    - Surface versus bulk
      - Backgrounds preferentially on surfaces, WIMPS interact anywhere
    - Electron versus nuclear recoil
      - Backgrounds cause electron recoils, WIMPS cause nuclear recoils
    - Multiple versus single scatter
      - Backgrounds multiple-scatter; WIMPS don't
  - Annual modulation
    - Surfing the WIMP "wind"
  - Diurnal modulation
    - Detect recoil direction
- Scale to large target mass
  - Maximize # of WIMP interactions
- Different target nuclei
  - Determine if possible signal from WIMPs or backgrounds

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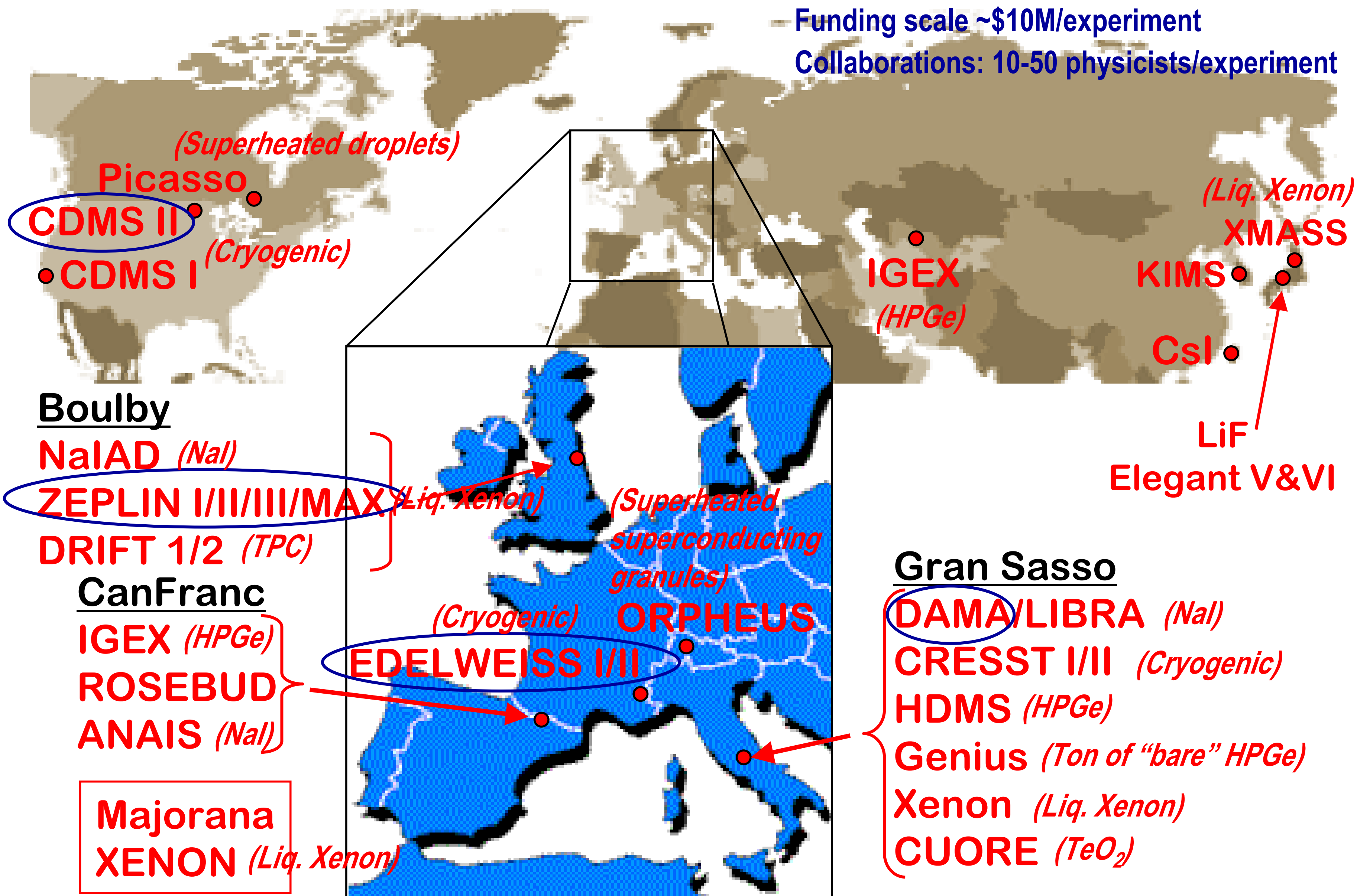
WIMP-detection Experiments Worldwide



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CDMS: An example of active background rejection

Dark Matter Search

Goal is direct detection of WIMPs which may be what holds our galaxy together

Cryogenic

Cool very pure Ge and Si crystals to < 50 mK using dilution refrigerator

Active Background Rejection

Detect heat and charge

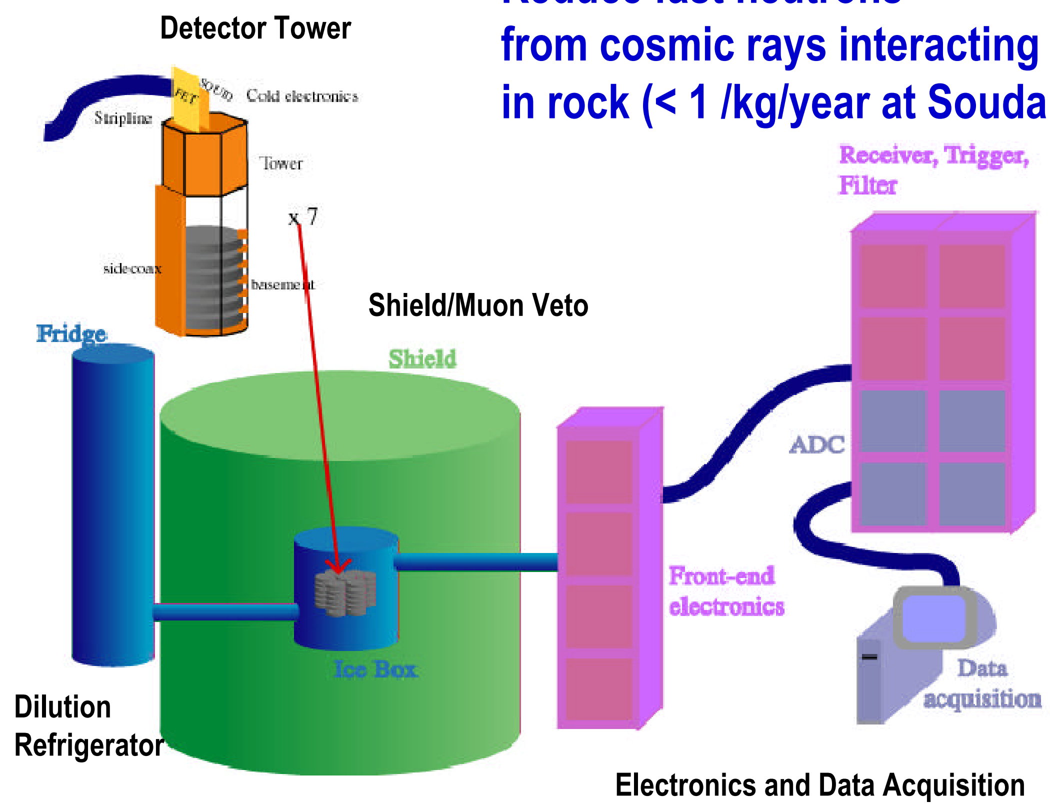
- WIMPS, neutrons => nuclear recoils
  - Charge/Heat ~ 1/3
- EM backgrounds => electron recoils
  - Charge/Heat = 1

Reject neutrons using

- multiple scattering
  - Neutrons do, WIMPS don't
- comparison of Ge to Si rates
  - Neutron cross sections similar, but WIMPs x5 higher in Ge

Deep Underground

Reduce fast neutrons from cosmic rays interacting in rock (< 1 /kg/year at Soudan)



Shielding

Layered shielding against radioactive backgrounds and active scintillator veto (>99.9% efficient against cosmic rays).

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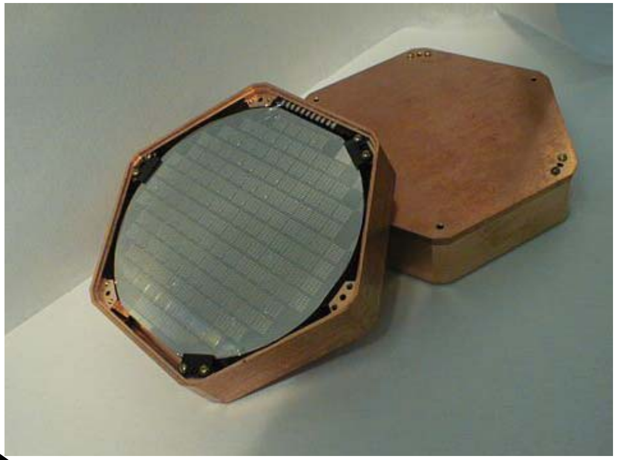
CDMS Detectors

Z-sensitive Ionization and Phonon Detectors

Low-voltage ionization measurement

Athermal phonon measurement

low-noise SQUID readout



Measured background rejection:

> 99.9% for EM backgrounds using charge/heat

> 98% for β's using pulse risetime as well

Better than expected in CDMS II proposal!

Tower of 6 ZIPs

Tower 1

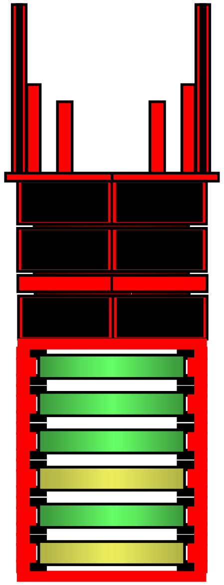
4 Ge

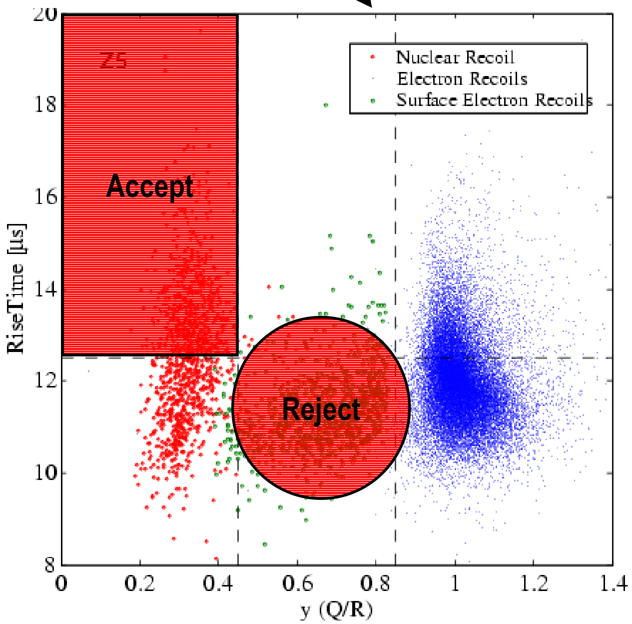
2 Si

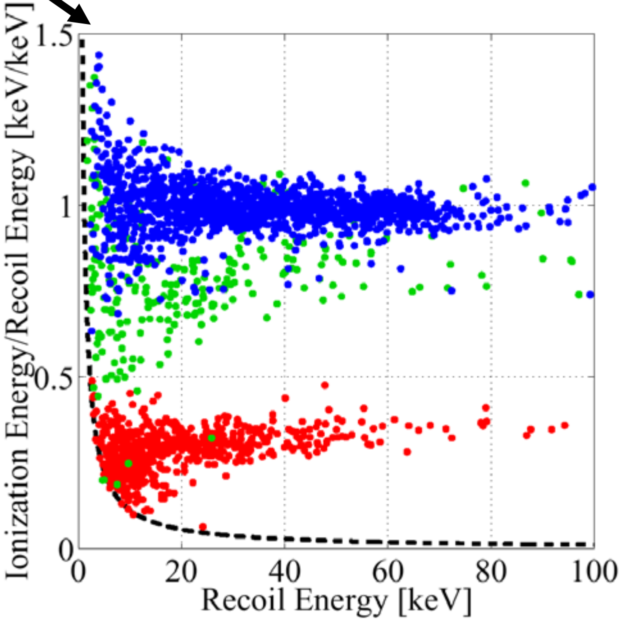
Tower 2

2 Ge

4 Si







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CDMS III: Reduced Backgrounds, Better Rejection

- Better/cleaner detectors that would capitalize on full CDMS II infrastructure (e.g. fill cryostat with 7 towers)
- Zero-background experiment is within reach
  - With 1000 kg-day exposure, would improve sensitivity by 10x
  - Would greatly improve evidence of a discovery
    - Cleaner results; no background subtraction systematics
    - Test distributions of signal events (energy, positions) vs. WIMP expectations
- Improve discrimination of detectors via modest changes
  - Phonon sensors on both sides of detectors (prototype made)
  - Interdigitated electrode design to tag surface events
  - Better phonon-sensor layout for position determination
- Reduce beta contamination via active screening/cleaning
  - Gas multiwire proportional chamber (prototype in progress)
  - Materials surface analysis (SIMS/Auger/TXRF) (in progress)
- Possibly improve active neutron shielding (under study)

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CryoArray: Scale to larger target mass

- Based on extrapolation of CDMS technology/strategy to 1 ton mass
  - Industrialize detector production with much less "extraneous" mass
- CDMS II/III (~5 kg y exposure) may have NO background
  - Increase mass to take advantage
  - Small background even for 1 ton mass seems realistic
- Detection goals for 1000 kg x 2 (live) years
  - ~100 WIMPs at 10^{-45}cm^2
    - ~10 WIMPs at 10^{-46}cm^2
  - ~10's background events

10^4 increase over present limits

10^2 – 10^3 increase over expts under construction

- Excellent discrimination so need little background reduction
  - Need to reduce external neutron background via shielding/depth
  - Need to reduce internal raw photon background rate only to best reached so far (by IGEX, H-M) for current rejection of 99.99%
  - Need to reduce internal β contamination by screening & cleaning surfaces to 2.5 x 10^{-2} counts/ (keV m^2 day) at current rejection efficiency of 99.5%
- Sufficient mass to do annual modulation search as well

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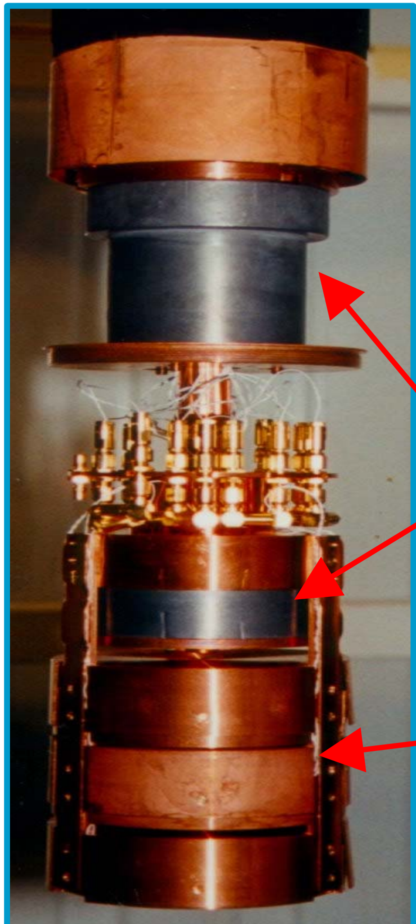
Other Cryogenic Experiments

Edelweiss

Similar technology to CDMS

1 kg: 2000-2003 -->9 kg: 2003-2006

Best current limits on high-mass WIMPs



Archeological lead

3 * 320 g Ge detectors: heat and ionization simultaneous readout (NTD thermistor)
Installed May 2002

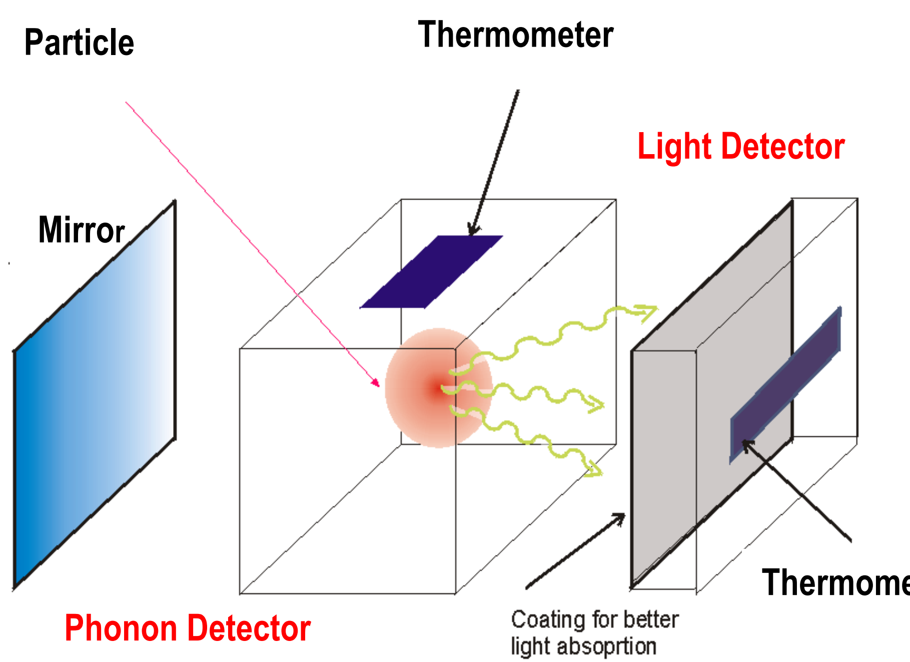
Cresst

Phonons + Scintillation

Results from a 6g $CaWO_4$ prototype

- No problem from surface electrons
- Very small scintillation signal
  - Scintillation threshold will determine minimum recoil energy

Scaling up to 300g detectors



DAMA NaI: Large target mass, no background rejection

Very elegant experimental setup - in place since 1996

Located at Gran Sasso Underground Lab (4000 mwe)
+ Photon and Neutron shielding

9 $\times$ 9.7 kg low-activity NaI scintillator crystals, each viewed by 2 PMTs

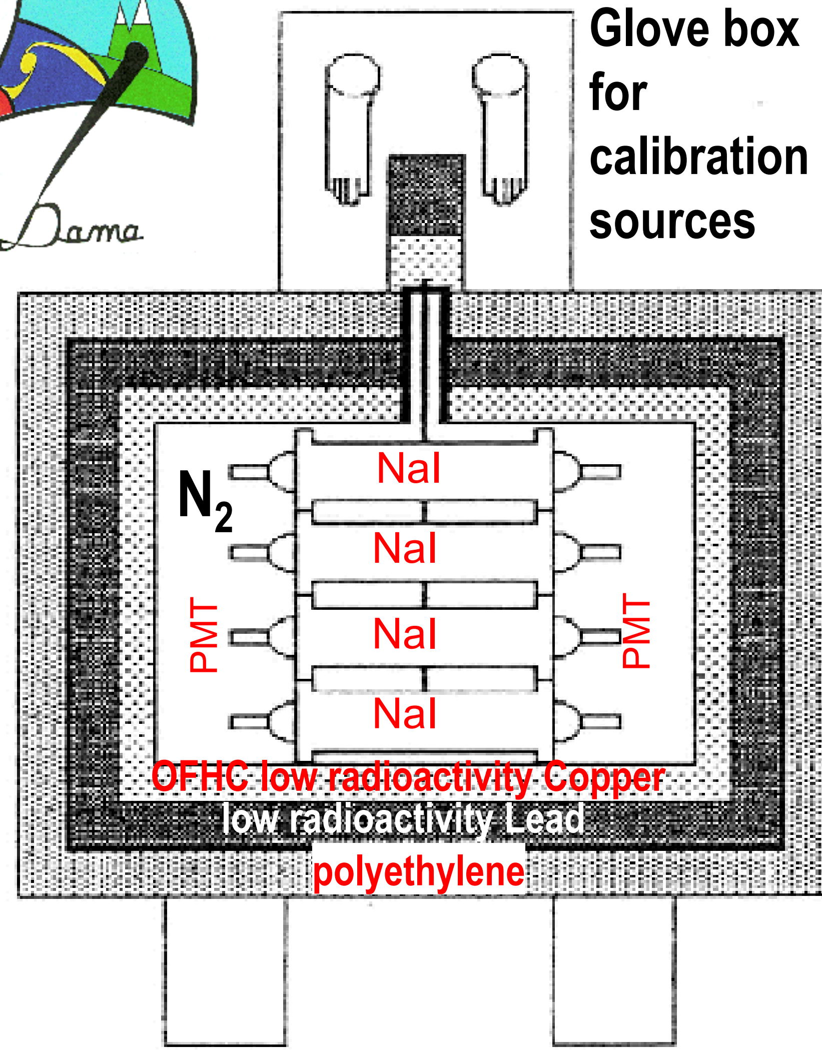
- Known technology
- Low cost
- Large mass
- Spin-dependent interactions

58,000 kg-days exposure through August 1999

See annual modulation signal!

New 250 kg experiment (LIBRA) in progress

Glove box for calibration sources



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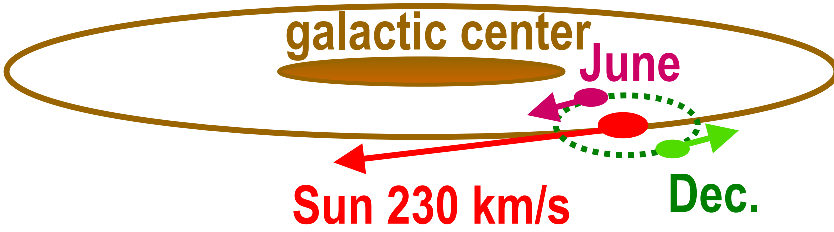
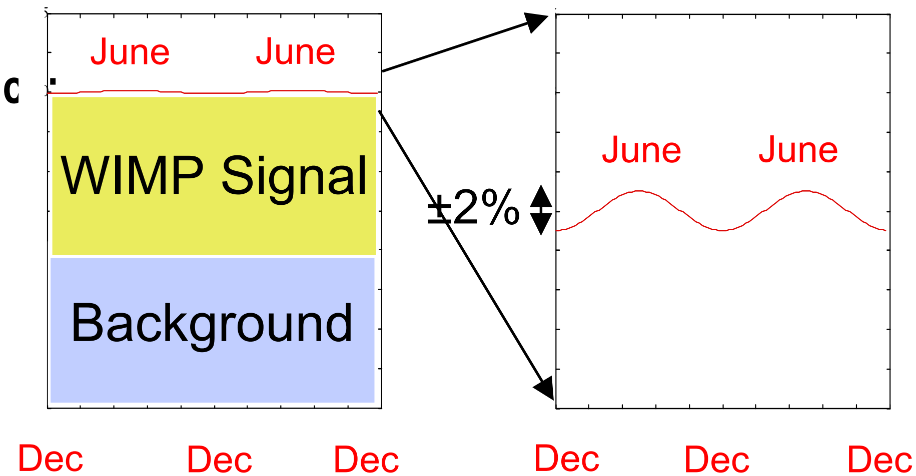
DAMA Search for Annual Modulation



Do not distinguish between WIMP signal and background directly

- Calculate the WIMP interaction rate from the amplitude of the modulation

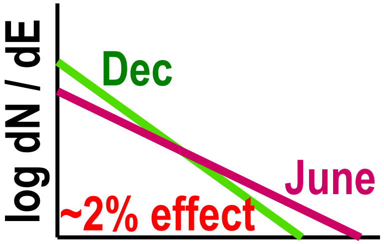


WIMP annual modulation signal characteristic

- Rate = cos(t)
- Low energies
- 1 year period
- Known phase
- Single hit
- Amplitude < 7% at maximum

Careful control of possible sources of background modulation

- Temperature variation (<<0.1%)
- Rn (no air)



Control of all possible systematic effects still difficult

- Near-threshold behavior of efficiency, energy linearity, and noise stability

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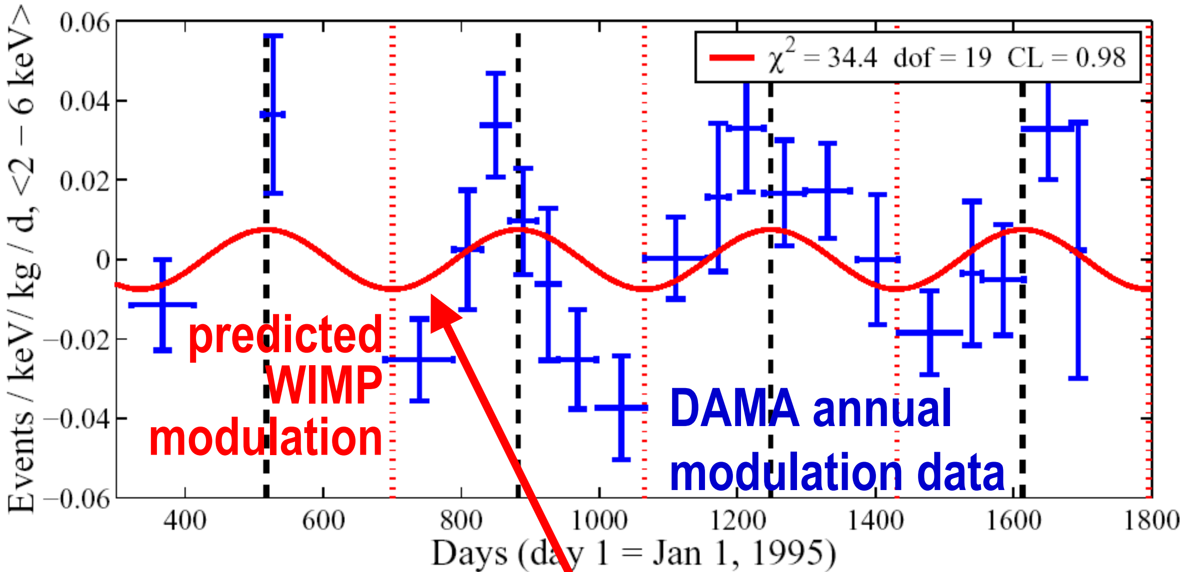
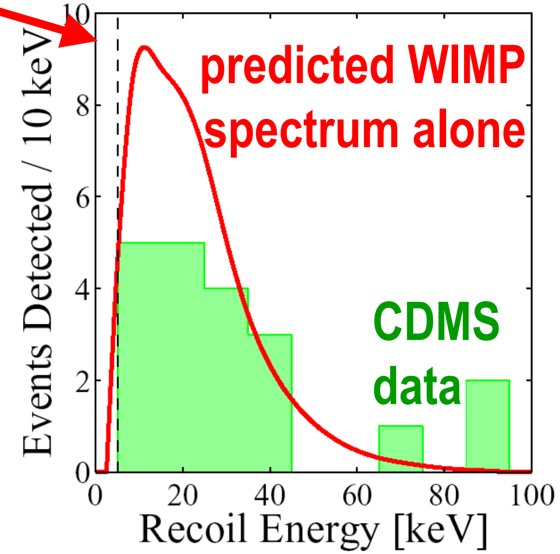
Incompatibility with DAMA



Test under assumptions of

- **"standard" halo**
- **standard WIMP interactions**

Best simultaneous fit to CDMS and DAMA predicts too little annual modulation in DAMA, too many events in CDMS (even for no neutron background)



CDMS results incompatible with DAMA model-independent annual-modulation data (left) at > 99.8% CL even if all low-energy events are WIMPs

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Liquid Xenon Detectors:
Compromise between large mass and background rejection

Potential to challenge cryogenic detectors

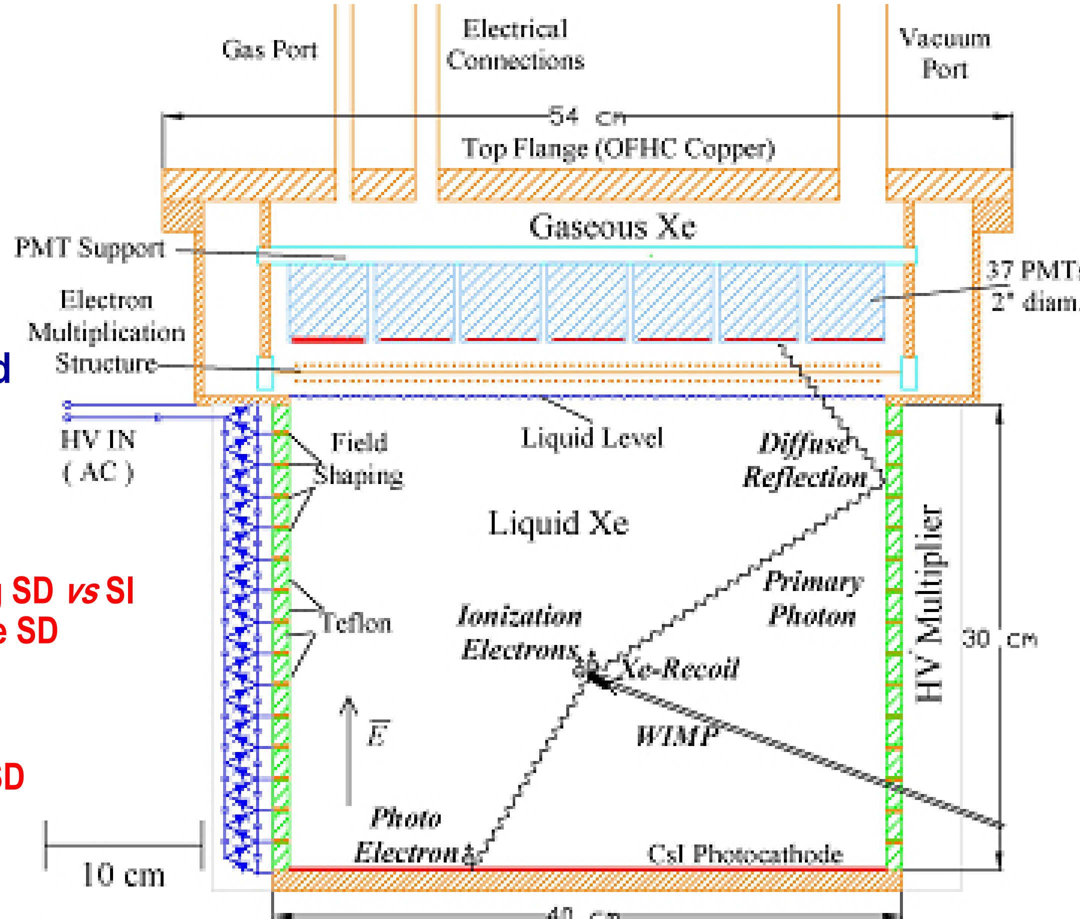
- Background rejection
  - Pulse shape discrimination now
  - R&D towards scintillation + ionization
- Scales more readily to high mass

Challenges

- Implement "dual-phase" to improve scintillation signal
- Ionization signal/noise poor near threshold

Several programs

- DAMA collaboration
  - Developed PSD in LXe
  - ^{129}Xe *vs* ^{136}Xe by using PSD → comparing SD *vs* SI signal to increase the sensitivity to the SD component
- Zeplin (UK/UCLA et al)
  - Preliminary results from 5 kg Xe using PSD
  - R&D proceeding towards 1 ton detector
- XENON expt (Columbia et al)
  - R&D phase I study towards 1 ton experiment
  - Based on earlier developments for LXeGRIT x-ray astrophysics



Columbia Univ.

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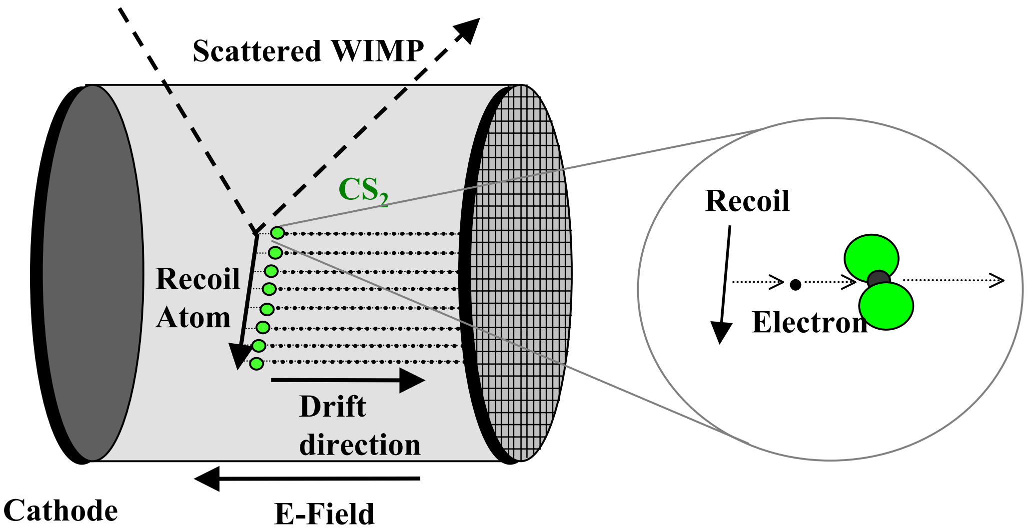
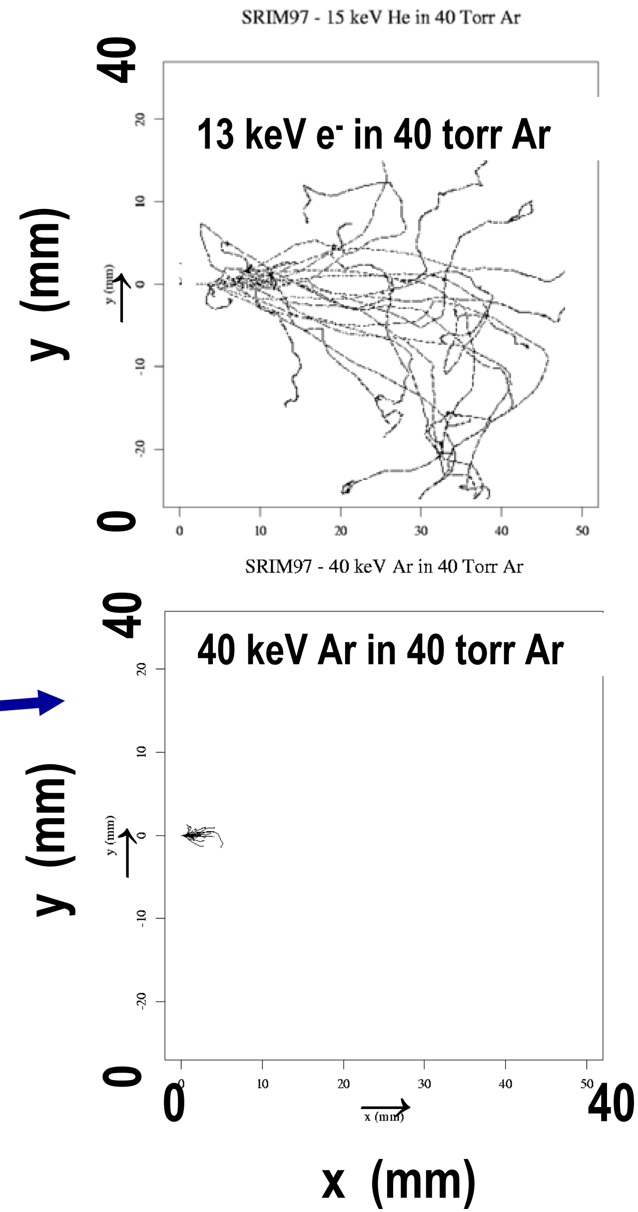
DRIFT: Look for signal directionality





- Sensitive to direction of recoiling nucleus
  - Diurnal modulation signal – galactic origin of signal
- Drift negative ions in TPC
  - No magnet
  - Reduced diffusion
- Electron recoils rejected via dE/dx, range
- DRIFT I
  - Cubic meter in Boulby since 2001
  - Engineering runs completed
- DRIFT II extension to 10 kg module proposed

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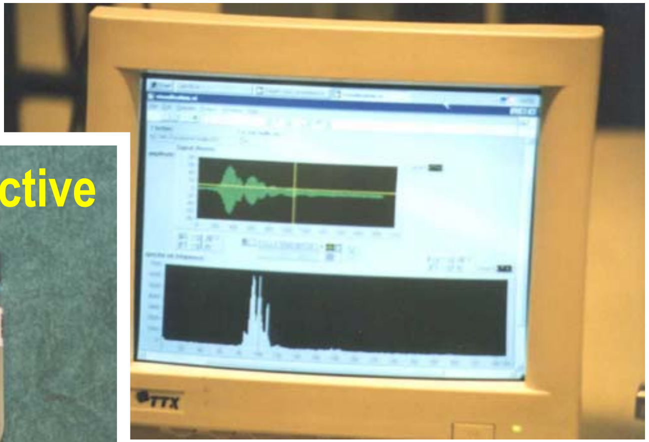
Picasso (Superheated Droplets): The Ultimate Background Rejection, but where's the mass?

- Superheated droplets, eg, freon, in a passive gel matrix – neutron dosimetry
  - Only high-ionization energy density tracks – nuclear recoils, alphas – sufficient to cause nucleation
  - Insensitive to gammas, betas, & minimum ionizing particles
  - Freon: ^{19}F – high *SD* coupling
- Challenges
  - Energy information – vary temperature in threshold detector
  - Materials issue – large A nucleus for spin-independent coupling
  - How to scale to large target mass
- SIMPLE Expt (Collar/Chicago)
  - Pioneering work
  - Emphasis on large A nucleus



Piezo-electric readout

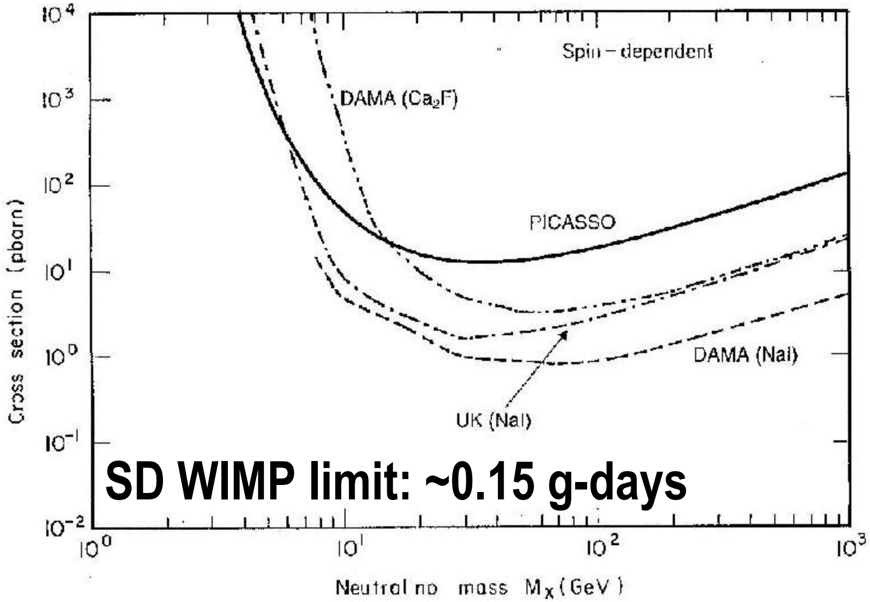
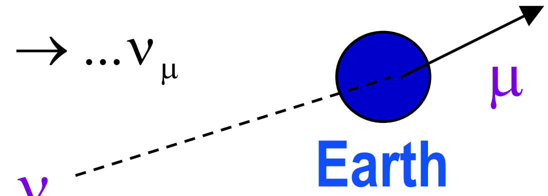


Fig.10

Indirect Detection of WIMPs

Annihilation of WIMPs in Sun (or Earth)

$$\chi\bar{\chi} \rightarrow q\bar{q} \rightarrow \ldots \nu_{\mu}$$

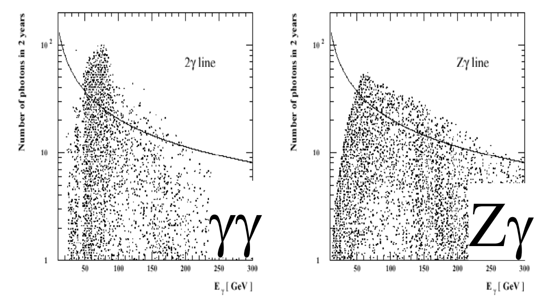


- Annihilation rate given by capture rate
- High for spin-dependent interaction with protons in sun
- Detectable by ν telescopes (km^3 volumes, good energy/angular resolutions)
  - Baksan, MACRO, SuperK,: already some sensitivity
  - Ice - AMANDA 10^4m^2, Ice Cube; Water - Baikal 2 x 10^3 m^2, NESTOR, ANTARES

Annihilation in Galaxy Center

$$\chi\bar{\chi} \rightarrow \gamma\gamma \qquad \chi\bar{\chi} \rightarrow Z\gamma$$

- Monoenergetic photons ($E \sim m_{\chi}$) but much lower rate
- Potentially detectable by gamma-ray telescopes
  - 10^5 m^2-scale with good energy resolution (VERITAS)
  - Smaller with excellent energy resolution (GLAST)



GLAST

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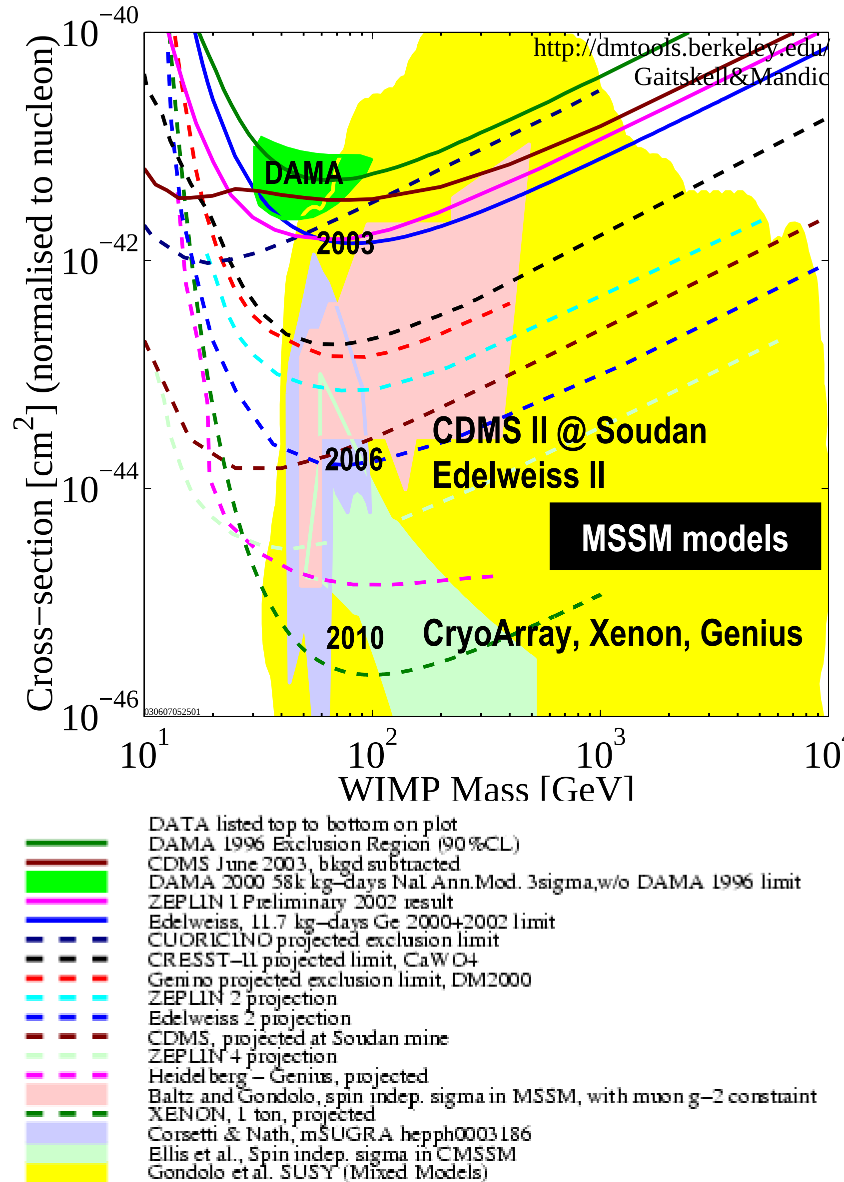
Summary and Projections

- **WIMPs**
  - May be significant fraction of Universe
  - New particle physics (SUSY neutralino)
    - Sensitive to 10-10000 GeV masses
    - Challenging MSSM models
- **Broad range of experimental approaches/efforts**
  - CDMS, Edelweiss, Zeplin
  - Dama/Libra + NaIAD – systematics or signal?
  - Many Others
- **Expansion to ton-scale**
  - ZepMAX, Cryoarray, XENON, GENIUS…
- **Growing scale of experiments**
  - Room for increased Fermilab participation
  - NUSEL - National Underground Science and Engineering Laboratory

90% CL upper limits assuming standard halo, A^2 scaling



Possible roles for Fermilab

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HEP participation - what can we bring?

- DAQ/electronics and cryogenics expertise (Primary Fermilab role in CDMS)
- Shielding (active and passive)
- Detector expertise (Liquid Xenon, NaI, TPC)

Support for CDMS through 2010

- Operations support (~ $0.5M / year)
- Explore neutron veto (liquid scintillator, lining cavern with chambers,…)
- Beta screening drift/cloud chamber (see beta contamination on surfaces)
  - Goal: Maintain linear sensitivity improvement for as long as possible

R&D on experimental techniques for the next stage of WIMP searches: 2010-2020

- CryoArray (based on CDMS technology)
- Liquid Xenon (some CDMS collaborators already participating)
- Drift (directional signal may be key, but how to get the target mass?)
  - Does it make sense to combine technologies at one site to help reject backgrounds?

Help make NUSEL a reality at Soudan

- Background screening facilities (α, β, γ, neutron) would be useful at present site
- Build deeper laboratory for next phase of WIMP search (2006-2010)
- Broad array of other uses ($\beta\beta$ decay, neutrino oscillations, neutrino astronomy,…)
- Leverage substantial Fermilab investment already at Soudan (CDMS, MINOS)